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Physical capacity and race performance of handcycle users

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Abstract—The purpose of this study was to determine physical capacity, gross efficiency (GE), and physical strain (PS) of 16 male handcycle users during a 10K race, and to relate these to race performance. All subjects used a handcycle system attached to their own wheelchair and were classified into a group with (A1/A2; N=10) and without (A3; N=6) upper-limb impairments. The PS was defined as the mean heart rate during the race, expressed relative to the heart rate reserve (%HRR). Race performance was defined as the mean race velocity (V_{race}). Maximal power output (PO_{max}), VO_{2peak}, and GE (at 28 W) were determined in a graded treadmill exercise test. PO_{max} (55±25 *versus* 129±26 W), VO_{2peak} (1.11±0.4 *versus* 2.12±0.4 $L.min^{-1}$) and V_{race} (13.6±3 *versus* 19.9±3 $km.hr^{-1}$) were different between A1/A2 and A3 ($p<0.001$), whereas PS (80±9 *versus* 88±9 %HRR; $p=0.12$) and GE (10.9±1.4 *versus* 9.7±0.9%; $p=0.09$) were not. PO_{max}, VO_{2peak}, and PS were associated ($p<0.05$) with V_{race} ($R=0.91$, 0.90, and 0.66). Regression analysis showed that after VO_{2peak}, GE added another 9 percent to the explanation of the variance of V_{race} ($R2=0.89$). In conclusion, attainable handcycling PO_{max} is markedly high and strongly related to race performance. The high PS during the race suggests that handcycling is well suited for aerobic training for most groups of wheelchair users.

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INTRODUCTION

Over the last decade, handcycling has become increasingly popular for sports and daily use activities for the wheelchair-user population. The application of an arm-crank propulsion system instead of the more traditional handrim propulsion system seems to allow for a greater mobility and for more sports potential of wheelchair users. It appears that individuals with low levels of physical capacity, such as persons with tetraplegia, could benefit especially from this relatively new wheelchair-propulsion technique.

In the 1980s, a limited number of studies showed that asynchronous (i.e., reciprocal) arm cranking (ACE) was mechanically more efficient than propelling a hand rim wheelchair system (1–4), results recently confirmed by Tropp et al. (5). Possibly due to a more continuous arm motion and power transfer and a more efficient muscle use, the stress on the cardiopulmonary system was lower during ACE than during wheelchair exercise at equal power output levels; lower oxygen uptake (VO_2), minute ventilation, stroke volume, heart rate, and systolic blood pressure have been reported (3,4). From these studies, it is evident that asynchronous ACE is a more efficient way of propulsion than handrim propulsion. Research into *synchronous* ACE, as is the case for contemporary handcycling, is relatively scarce (6,7).

Hence, suggested benefits from handcycling, including increased efficiency, performance, and range of action, could at least in part be substantiated by data from research on arm crank ergometers. However, one should be careful to extrapolate these data to actual handcycling, since this type of exercise can differ from ACE in several ways, related to factors such as seat position, the need to steer, stability, crank type/position, and the possibility of changing gears. Research on actual synchronic handcycling, however, is still very scarce. Until now, it is not known what physical performance (maximal power output and aerobic power levels) can be achieved in users of these systems and to what extent this performance is related to the degree of disability. Also, no information is currently available on the efficiency of synchronic handcycling, on the physical strain during handcycling, and on the potential role of handcycling in increasing physical capacity of wheelchair users.

The purpose of the current descriptive study, therefore, was to determine physical capacity parameters of wheelchair users with different disabilities during handcycling, as well as to ascertain gross efficiency (GE) of handcycling under standardized conditions. Also, the physical strain (PS) during a 10-km handcycling race was determined. A second purpose was to study to what degree these parameters are determinants of handcycling race performance.

METHODS

Subjects and Handcycle

Sixteen male wheelchair users (**Table 1**) volunteered to participate and signed an informed consent form approved by the ethical committee of the Rehabilitation Center Amsterdam. For the race, subjects were classified into a group with (A1/A2; N=10) and without (A3; N=6) upper-limb impairments (8). The A1/A2 group contained all individuals with tetraplegia, whereas A3 consisted of two individuals with paraplegia, two with spina bifida, one with double transfemoral amputations and one with lower limb joint problems. Average weekly handcycle training was 2.3±3.4 hours, and total weekly exercise training (including handcycle training) averaged 4.2±3.1 hours. Each subject completed a medical history questionnaire before performing the exercise test. All subjects indicated feeling healthy with no secondary pathology.

During the race and the graded exercise test (see below), all subjects used their own modular handcycle system that could be attached to their everyday wheelchair (see **Figure 1**). This commercially available system is designed for the beginning handcycle rider or recreational athlete. Since each subject used his own handcycle system, its configuration varied among subjects. Eight subjects had regular type (straight) cranks, while the other 8 had wider (curved) cranks. All A1/A2 subjects, except for subject number 8, had pedals designed for individuals with limited hand function, whereas all A3 subjects had regular T-handles. Ten subjects had 20-inch front wheels, 4 had 12-inch wheels, 1 had a 7-inch wheel, and 1 had a 24-inch wheel.

Handcycling Race

All subjects participated in the Dutch Open 10-km handcycling championships, held September 1999 in the

Figure 1.
Subject during the graded exercise test on the motor-driven treadmill while metabolic data is being collected.

Vondelpark, Amsterdam. The A1/A2 group started separately (1.5 hours earlier) from the A3 group. During the race, heart rate (HR) was continuously recorded using a Polar Vantage NV (Polar, Kempele, Finland) and a 5-s storing interval. The PS was defined as the mean HR above resting HR during the race, expressed as a percentage of the individual's heart rate reserve (HRR; reference 9). The HRR was defined as the range between the lowest HR recorded just before the exercise test (see below) and the highest HR recorded during the exercise test or during the race. Race performance was defined as the mean race velocity (V_{race}).

Physical Capacity and Gross Efficiency

Within 2 weeks after the race, subjects reported to the university laboratory to perform a graded maximal exercise test on a motor-driven treadmill (Enraf Nonius 3446, Netherlands, belt 1.25 * 3.0 m). Before the exercise test, rolling resistance of the handcycle-user combination was determined in a drag test at the actual exercise test velocity (2). After a 5-minute rest and a subsequent 5-minute warm-up, two 3-minute submaximal exercise bouts were performed interspersed by a 1-minute rest. All subjects from A3 and subjects 9 and 10 from A1/A2 performed these bouts at a target power output of 28 W and 38 W. The remaining A1/A2 subjects performed these tests at 18 W (N=5) and/or 28 W (N=5), depending on their estimated physical capacity.

After the submaximal exercise periods and a 1-minute rest, workload was increased every minute by applying extra resistance to the back of the wheelchair using a pulley system. Using this system allows for accurate setting of total resistance and eliminates the need to use a ramp or high velocities for increasing workload (10,11). The PO increments were 5 W and 10 W for A1/A2 and A3, respectively. Treadmill belt velocity was kept constant throughout the test. To keep cadence between 60 and 70 rpm, gearing ratio and belt velocity were individually adjusted, which resulted in differences in belt velocity among the subjects: 6 $km.hr^{-1}$ for 13 subjects, 5 $km.hr^{-1}$ for 1 subject and 7 $km.hr^{-1}$ for 2 subjects. Cadence was on average 63.5±4.5 rpm.

Maximal power output (PO_{max}) was the highest PO (calculated from rolling plus extra resistance and belt velocity) that could be maintained for more than 30 s. Oxygen uptake (VO_2), carbon dioxide production (VCO_2), and minute ventilation (VE) were continuously monitored with an Oxycon Alpha (Jaeger, Bunnik, The Netherlands) calibrated before each test with a known reference gas mixture. Peak values were defined as the highest 30-s average values during the test. The HR was continuously monitored with the Polar Vantage NV. Resting HR was defined as the lowest HR recorded during the 5-minute pre-test rest period and HR_{max} was defined as the highest 5-second value recorded during the test.

For the submaximal exercise periods, GE was calculated during the third minute from the energy expenditure (Pi, derived from VO_2 and RER according to Garby and Astrup (12)) and PO: GE=PO/Pi $\times$ 100 percent.

Data Analysis

A Student's t-test was used to identify differences in relevant subject characteristics, PO_{max}, VO_{2peak}, GE, V_{race}, and PS between groups A1/A2 and A3. Two-tailed Pearson correlation coefficients between V_{race} and body mass, GE, VO_{2peak}, and PO_{max} were calculated. A stepwise multiple regression analysis, using PO_{max}, VO_{2peak}, GE, PS, body mass, and classification as independent variables, established the most important determinants of V_{race}. Significance level was set at 0.05.

RESULTS

No significant differences between the groups were found for age, body mass, duration of disability, and weekly training hours (**Table 1**). Group A1/A2 had significantly longer experience with handcycling than group A3. **Table 2** shows individual HR and V_{race} data collected during the race. Due to practical problems, HR during the race was not recorded in two subjects. Although V_{race} was significantly ($p<0.01$) lower in A1/A2 than in A3, average PS was not significantly ($p=0.12$) different.

All subjects completed the maximal exercise test without problems. Rolling resistance was on average 7.4±2.4 N. For A1/A2 and A3, respectively, values were 7.2±2.8 N and 7.9±1.8 N ($p=0.58$). GE was 8.3±0.8 percent at 18 W (N=5), 10.3±1.4 percent at 28 W (N=13), and 11.5±0.8 percent at 38 W (N=8). GE at 28 W tended to be higher ($p=0.09$) in A1/A2 than in A3 (**Table 3**). Cadence was similar for the two groups (A1/A2: 63.6±6.1 rpm; A3: 63.3±1.6 rpm)

Table 3 provides results from the graded exercise test. Average values for PO_{max}, VO_{2peak}, and VE_{peak} were significantly lower in A1/A2 than in A3 ($p<0.001$). Ten of 14 subjects (71 percent) had a higher HR_{peak} during the race than during the exercise test. A paired t-test showed that on average HR_{peak} was significantly ($p=0.04$) higher

Table 1.
Subject characteristics

Subject	Group	Age (yrs)	Body Mass (kg)	Disability	Duration of Disability (months)	Handcycle Use (months)	Handcycle Training (hrs. week^{-1})	Total Training (hrs. week^{-1})
1	A1/A2	42	70	SCI, C6/7	276	48	4	4
2	A1/A2	54	75	SCI, C7	62	50	0	3
3	A1/A2	21	52	SCI, C5#	39	34	4	6.5
4	A1/A2	25	78	SCI, C5/6	150	45	0	2.5
5	A1/A2	25	79	SCI, C5/6	85	36	1	3
6	A1/A2	42	75	SCI, C5	122	36	5	5
7	A1/A2	29	77	SCI, C7/8	39	24	0	3
8	A1/A2	29	90	SCI, C6/8	100	60	0	0
9	A1/A2	50	94	SCI, C6#	63	33	12.5	12.5
10	A1/A2	37	92	SCI, C7	230	60	3	6.5
11	A3	53	86	SCI, T10	29	17	0	0
12	A3	27	74	Joint problems	132	40	0	2.5
13	A3	53	99	2BKA	52	36	0	2
14	A3	33	64	SCI, T4	15	9	5	7
15	A3	34	79	Spina bifida	411	3	0	2.5
16	A3	36	74	Spina bifida	443	48	2	6.5
	A1/A2	35±11	78±12		117±81	43±12	3.0±3.9	4.6±3.4
	A3	39±11	79±12		180±196	26±18*	1.2±2.0	3.4±2.7
Total		37±11	79±12		141±133	36±16	2.3±3.4	4.2±3.1

*Significantly different from A1/A2; SCI=spinal cord injury; #=incomplete lesion; BKA=below-knee amputation.

Table 2.
HR data and race performance (V_{race}) from the 10K handcycle race. Means ± standard deviations

Group	N	HR_{peak} (bpm)	HR_{avg} (bpm)	Physical Strain (%HRR)	V_{race} (km·hr^{-1})
A1/A2	9	127.3±19.2	115.4±18.0	80.2±8.8	13.6±3.2
A3	15	182.8±13.2*	171.6±13.5*	88.4±8.9	19.9±2.7*
Total	14	147.1±32.3	135.5±32.2	83.1±9.4	16.0±4.3

*Significantly different from A1/A2.

Table 3.
Results from the maximal graded exercise test

Group	HR_{max} (bpm)	$VO2_{peak}$ (L.min^{-1})	$VO2_{peak}$ (mL.kg^{-1}min^{-1})	PO_{max} (W)	PO_{max} (W.kg^{-1})	GE at 28W	RER-max
A1/A2 (N=10)	118.2±17.2	1.11±0.4	14.2±3.8	55±25	0.72±0.30	10.9±1.4	1.14±0.10
A3 (N=6)	181.7±10.3*	2.12±0.4*	27.1±6.0*	129±26*	1.64±0.32*	9.7±0.9	1.29±0.03*

N=7; *Significantly different from A1/A2.

during the race (147.1±32.3 bpm) than during the test (139.9±33.7 bpm). **Figure 2** displays an example of a HR recording of a subject with tetraplegia during the race and during the exercise test.

PO_{max}, VO_{2peak}, and PS were significantly ($p<0.05$) associated with V_{race} (**Table 4**). **Figure 3** shows the relationship between PO_{max} (W) and V_{race}. Results of the regression analysis indicated that after VO_{2peak}, GE at 28 W added another 9 percent to the explanation of the variance of V_{race} (multiple R2=0.89), with the calculated regression equation being $V_{race}=7.30 \times 10^{-3}\ VO_{2peak} + 1.08\ GE - 6.03$. **Table 5** shows calculated regression equations to predict V_{race} using PO_{max} and VO_{2peak} as independent variables.

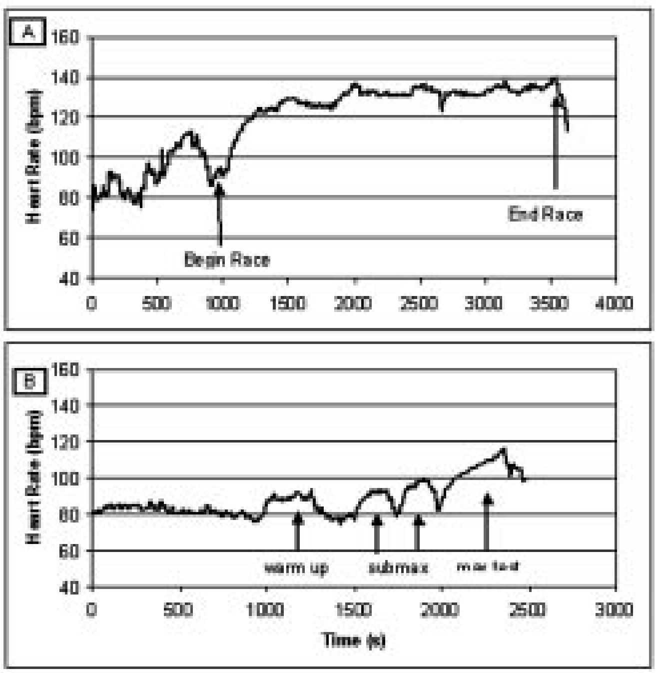

Figure 2.
Example of a heart rate (HR) recording of a subject with tetraplegia during the race (A) and the graded exercise test (B).

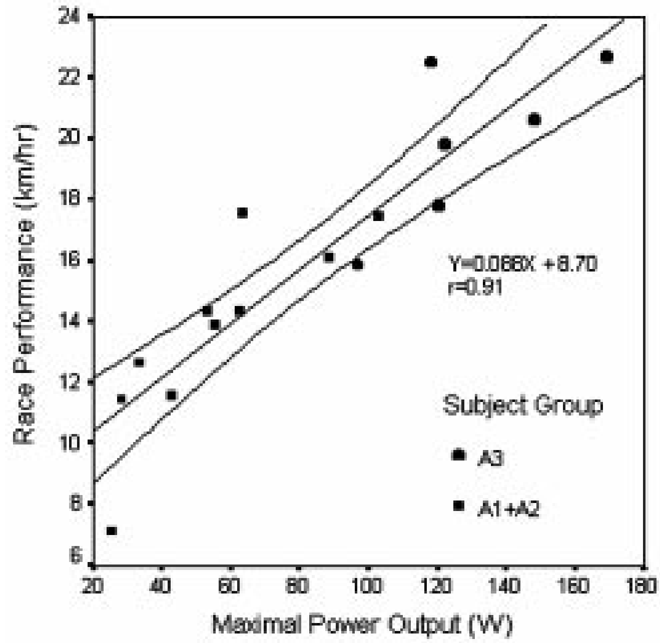

Figure 3.
Relationship between maximal power output and race performance for the two subject groups. The regression equation is calculated using data from all subjects (N=16).

DISCUSSION

Handcycling Race

As expected, race velocity was significantly higher in A3 than in A1/A2. The average 19.9 $km \cdot hr^{-1}$ velocity for the A3 group indicates that fast velocities can be achieved, especially when considered that all subjects in the present study used an attach-unit handcycle system, a system designed for the recreational user and not specifically made to achieve high velocities. In addition, the present subjects were not highly trained athletes; for most (12 of the16) subjects, this was the only competitive race that year. In comparison, the winners of the race (not

Table 4.
Two tailed Pearson correlation coefficients between race performance and age, body mass, physical strain during the race (PS-race), GE, VO_2peak, and PO_{max}. N=16

	Body Mass	PS-race (%HRR)	GE (at 25W)	VO_2peak ($1.min^{-1}$)	VO_2peak ($mL.kg^{-1}$ min^{-1})	PO_{max} (W)	PO_{max} ($W.kg^{-1}$)
Race Performance ($km.hr^{-1}$)	0.15	0.66*[#]	-0.23[t]	0.90**	0.88**	0.91**	0.89**

*p<0.05; **p<0.01; #N=14; [t]N=13

Table 5.
Regression equations to predict race performance (V_{race}) using parameters of physical capacity (PO_{max} and VO_{2peak}).

Group	Dependent Variable	Regression Coefficients + Intercepts	Independent Variable	P	R^2
Total (N=16)	V_{race}	0.088±0.01	POmax (W)	0.000	0.83
		8.70±0.96		0.000	
Total (N=16)		$6.06*10^{-3}$±0.00	VO_2peak ($L.min^{-1}$)	0.000	0.81
		6.96±1.27		0.000	

included in this study) were well-trained athletes using rigid-frame handcycles averaging 23.7 (A1/A2) and 34.5 (A3) $km \cdot hr^{-1}$. Taking this into account, the relatively high average velocities attained with the attach-unit systems indicates that these systems are well suited for outdoor use, even for those with limited upper-body function, increasing the users' freedom of motion and level of independence.

Despite the difference in race performance, there was no significant difference in physical strain during the race for the two groups, signifying an equal degree of effort. The high levels of PS are of similar magnitude as those described for wheelchair racing and basketball, and considerably higher than reported for wheelchair tennis, volleyball, table tennis, and racquetball (13–15). The lowest average PS recorded was 66 percent, indicating that handcycling can induce an adequate aerobic training stimulus for individuals both with and without upper-body impairment.

A remarkable finding was that the majority of subjects achieved higher HR_{peak} levels during the race than during the exercise test. These differences, which could be large (up to 28 bpm), especially in the A1/A2 group, are not easily explained. The authors feel that all subjects performed maximally on the exercise test, supported by the high RER values at maximal exercise (1.19±0.11, range 0.99–1.34). This should have resulted in maximal HR values. The fact that the race was longer in duration than the test, potentially resulting in higher HR values due to cardiovascular drift, may explain some but not all differences, since the majority of subjects had HR values at or above exercise test peak levels just after the start of the race (see **Figure 2**). Although subjects used the same handcycle during the race and test, the way they performed the test may also have differed from the movement pattern during the race. Not only did we impose a constant cadence that may have been different from a freely chosen one and hence race cadence, but there was also limited time to relax the arms and shoulders. The present protocol, therefore, may have induced more (or earlier) local fatigue than would occur during the race, and consequently, test performance may have been somewhat lower. If this is the case, one could conclude that this protocol is not optimal to determine maximal HR levels in this population, and that physical capacity may have been underestimated in this study. Further research is required to elucidate these results.

Physical Capacity

VO_{2peak} values were comparable to values reported for similar populations (16,17). In contrast, PO_{max} values found in this study were remarkably high; i.e., approximately twice the values normally reported for wheelchair ergometry in similar mixed populations (11) and even higher than wheelchair ergometry values for highly trained wheelchair athletes (18,19). The measured PO is probably even an underestimation of the actual PO during the exercise test, since factors such as chain friction and inertia due to upper-body motion are not measured during the drag test. Simple chain transmission can cause energy losses of about 1.5 percent (20). Taking into account that these individuals were not young well-trained athletes and that these attach-unit handcycles were not made for high PO levels, it can be concluded that these systems allow for high PO levels even in the general wheelchair population.

The fact that differences in PO_{max} for the two modes can be large, was shown by subject number 2, who performed a wheelchair exercise test within a month of the handcycling test and attained only 30 W compared to the 53W for handcycling. In addition, VO_{2peak} achieved during the wheelchair test was considerably lower (0.7 $L \cdot min^{-1}$) than achieved during the handcycle test (0.95 $L \cdot min^{-1}$), suggesting that at least part of the higher handcycle PO is due to a larger muscle mass that can be activated. This result also suggests, at least for individuals with limited hand function, that handcycle exercise tests might evoke higher VO_{2peak} levels than wheelchair ergometry tests, which is in contrast with previous comparisons between arm cranking and wheelchair exercise (4,21,22). In addition, due to the higher VO_2 levels, it seems that handcycling can provide a better aerobic training stimulus in this population. However, more definitive research is needed to substantiate these suggestions.

Not too long ago, individuals with a limited physical capacity used to be at great risk of ending up in an electric wheelchair as a result of the insufficient handrim wheelchair PO they could achieve. A PO of 15–25 W, common in individuals with higher levels of tetraplegia (11,23,24), is generally insufficient to propel a wheelchair outside for longer periods, limiting the user's range of action. However, with these handcycle systems PO as well as attainable velocities that can be achieved are markedly higher. This enables wheelchair users to increase their range of action and reduce their dependency on others for performing daily activities. In addition, the handcycle probably allows for more activation of available muscle mass, which could provide for a better aerobic training stimulus, potentially resulting in higher fitness levels and reduced risk of secondary medical complications.

Gross Efficiency

Gross efficiency (GE) values were higher than values normally reported for manual wheelchair propulsion at this relatively low PO (2,25). The average values of 10.3 percent at 28 W and 11.5 percent at 38 W are similar to values found for arm cranking and crank propelled wheelchair exercise at the same low PO levels (2,26). The values found may well be somewhat underestimated, since important efficiency-affecting factors such as cadence and velocity were imposed on the riders, which may have resulted in less than optimal efficiencies for these individuals. An unexpected result was that GE was not different between groups, since lower efficiencies have been found in those with tetraplegia for wheelchair exercise, at least partially the result of a lower effectiveness of force application (27). Hence, one could have expected a lower GE in group A1/A2, but in contrast there was a tendency towards a higher efficiency in this group. Apparently, the handcycle system enables these individuals to use the available energy to the same extent as those without limited arm function. This could in part be explained by the use of quad pedals, which allows individuals with limited hand function to better transfer the force generated in the shoulders and elbows to the crank system, possibly resulting in higher efficiencies and PO_{max} levels. In addition, these pedals, combined with the more continuous and fluent power transfer, may result in a lower prevalence of hand-wrist injuries, common in handrim wheelchair propulsion.

Determinants of Race Performance

As expected, it was found that physical capacity (absolute PO_{max} and VO_{2peak}) was the best predictor of race performance, explaining over 80 percent of the variance. In contrast to these results, Cooper could not find a significant relation between VO_{2peak} and 10-km wheelchair race performance in 11 wheelchair athletes (28), an apparently contradictory result that could be explained by the homogeneity of his subject group. In agreement with our results, he found that speed at VO_{2peak} (measure of PO_{max}) and GE were significantly related ($r=-0.66$ and -0.56, respectively) to race time. Our results also indicate that after physical capacity, GE additionally explains 9 percent of the variance in race performance. The regression equation shows that an increase in GE of 1 percent is related to a 1-km·hr^{-1} higher race velocity. Other factors that were not taken into account, such as race tactics (e.g., drafting), may explain the additional variance in race performance. The results from the regression analyses also suggest that this handcycle test may be a useful tool for evaluating training programs and for predicting race performance in this population. However, results must be interpreted cautiously, since the number of subjects used in these regression analyses is relatively small.

CONCLUSION

In conclusion, it was shown that maximal power output levels that can be achieved during handcycling are remarkably high. Also, 10-km handcycle race performance was closely related to the physical capacity of handcycle users. The high physical strain during the race suggests that this mode of exercise is well suited for aerobic training for most groups of wheelchair users, including those with limited arm function.

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